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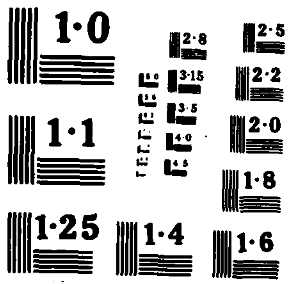
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STRUCTURES REPORT 414

A NUMERICAL INVESTIGATION INTO THE PLASTIC STRESS AND STRAIN FIELDS AROUND A SURFACE CRACK

by

R. JONES M. HELLER
Aeronautical Research Laboratories,
Defence Science and Technology Organisation,
Melbourne, Australia

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SUMMARY

This paper presents two finite element approaches for the three dimensional elastic-plastic analysis of a surface crack. The distributions of the stress and strain fields around the crack are discussed in detail and it is shown that both approaches yield similar values for the strain energy distribution around the crack.

POSTAL ADDRESS: Director, Aeronautical Research Laboratories,
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NOTATION

$\mathbf{u}$	Vector of nodal displacements
$\mathbf{C}(u)$	System of constraint equations
J	Path independent line integral around crack tip
K_σ	Plastic stress intensity factor
K_ϵ	Plastic strain intensity factor
$\mathbf{K}_p$	Penalty element stiffness matrix
$\mathbf{L}$	Matrix of coefficients in system of constraint equations
n	Exponent in power law hardening equation
P	Penalty number
r	Distance from crack tip
S	Strain energy density function
u	Displacement
u'	Required displacement function
u_i	Displacement component
W	Strain energy density
X	Local isoparametric coordinates
x, y, z	Cartesian co-ordinate system
α	Constant in power law hardening equation
ϵ_{ij}	Strain tensor
ϵ_o	Reference value of strain
σ_{ij}	Stress tensor
σ_o	Reference value of stress
Π^*	Global potential energy functional

1. INTRODUCTION

In recent years a great deal of work has been undertaken in order to characterize the elastic and plastic stress strain fields around a crack which is either in plane strain or plane stress [1–4]. A number of criteria for assessing severity have been proposed; of these the J integral approach [3] and the strain energy density factor (viz., S) approach [5] are widely used and it has been shown that S and J are linearly proportional.

The purpose of the present paper is to develop a methodology for three dimensional elastic–plastic finite element analysis and to investigate whether the functional form of the two dimension solution is valid for a three dimensional crack.

2. TWO DIMENSIONAL ANALYSIS

Let us consider a material for which the relationship between stress and strain in simple tension, is given by:

$$\epsilon/\epsilon_0 = \alpha(\sigma/\sigma_0)^n \tag{2.1}$$

where α is a dimensionless constant and σ_0 and ϵ_0 are reference values of the stress and strain. In plane strain the stress, strain and displacement fields of the dominant singularity at the crack tip have the form:

$$[\sigma_{ij}, \sigma_e] = \sigma_0 K_\sigma r^{-1/n+1}[\hat{\sigma}_{ij}(\theta), \hat{\sigma}_e(\theta)] \tag{2.2}$$

$$\epsilon_{ij} = \alpha\epsilon_0 K_\epsilon r^{-n/n+1}\hat{\epsilon}_{ij}(\theta) \tag{2.3}$$

$$u_i = \alpha\epsilon_0 K_\epsilon r^{1/n+1}\hat{u}_i(\theta) \tag{2.4}$$

where r is the distance from the crack tip and θ is the angle measured from directly ahead of the crack tip. The dimensionless functions $\hat{\sigma}_{ij}$, $\hat{\sigma}_e$, $\hat{\epsilon}_{ij}$ and $\hat{u}_i$ depend on the strain hardening exponent n and have been given in [1]. The plastic stress and strain intensity factors K_σ and K_ϵ ($= K_\sigma{}^n$) are related to the J integral by:

$$J = \alpha\sigma_0\epsilon_0 K_\sigma K_\epsilon I$$

$$= \alpha\sigma_0\epsilon_0 K_\sigma{}^{n+1} I$$

where I is only a function of n and is tabulated in [1]. The strain energy density W in the direction $\theta = 0$, i.e. ahead of the crack, defined by:

$$W = \int_0^{\epsilon_{ij}} \sigma_{ij} d\epsilon_{ij} \tag{2.6}$$

is related to K_ϵ and K_σ by

$$W = \frac{\alpha}{r}\sigma_0\epsilon_0\left(\frac{n}{n+1}\right)K_\sigma{}^{n+1} \tag{2.7}$$

so that the strain energy density function S, where $S = rW$, can be directly related to J by the equation:

$$S = \frac{Jn}{I(n+1)}. \tag{2.8}$$

In deriving equations (2.2), (2.3) and (2.4) references [1–4] used several simplifying assumptions. Indeed, these equations are only valid for monotonic loading. Nevertheless, this representation is commonly used.

If the stress–strain relationship is assumed to be piecewise-linear, rather than as given in equation (2.1), then the stresses exhibit an r^{-1} variation at the crack tip [1], rather than the $r^{-1/n+1}$ variation mentioned previously. However, predictions for the strain energy density W, and hence S and J, at the crack tip are relatively insensitive to the assumed stress–strain relationship.

For the special case when $n = 1$ and the material is purely elastic, the above equations reduce to the well known equations for two-dimensional linear elastic fracture mechanics. In linear elastic fracture mechanics theory the functional form of the stress field around a three dimensional crack is the same as that around a crack in two dimensional plane strain. This raises the possibility that in three dimensional elastic–plastic fracture mechanics, the functional form of the stress and strain fields may be similar to that given in equations (2.2), (2.3) and (2.4).

3. A PENALTY FOR ELASTIC–PLASTIC FRACTURE

Let us now assume that the displacements around a three dimensional crack have the functional form given in equation (2.4). This assumption can be built into the standard finite element method in a variety of ways, the simplest of which is the penalty approach [6], which we will now term method A. In this approach we minimize the constrained functional Π^* (see Appendix) where

$$\Pi^* = \Pi + \sum_{i=1}^{3} P \iiint W(x, y, z)(u_i - u_i')^2 dv \tag{3.1}$$

and where Π is the complementary potential energy, P is the penalty number, $W(x, y, z)$ is a positive weighting function, u_i are the components of the displacement field around the crack for a standard isoparametric element, whilst u_i' are the expressions for the near tip displacement field as given in (2.4).

When P becomes large the constraint $u_i = u_i'$ is enforced. In this work, fifteen-noded isoparametric wedge elements were used around the crack tip and different weighting functions evaluated. However, based on physical grounds, the approach adopted was to use reduced integration, as required in [6], and set

$$\begin{aligned} W &= 1 \text{ at the nodes and at the near tip Gauss points} \\ &= 0 \text{ at all other points.} \end{aligned}$$

In the next section, the validity of this approach will be evaluated by comparing, amongst other things, the values for the strain energy density function S computed from the elements in front of the crack tip elements, with the value of S computed using the relationship

$$\begin{aligned} S &= \alpha\sigma_0\epsilon_0 \frac{n}{n+1} K_\sigma^{n+1} \\ &= \alpha\sigma_0\epsilon_0 \frac{n}{n+1} K_\epsilon^{(n+1)/n} \end{aligned} \tag{3.2}$$

where K_ϵ is evaluated from the opening of the crack, i.e. using equation (2.4).

3.1 Alternative Computational Methods

A variety of methods have been developed for the finite element analysis of two dimensional elastic–plastic fracture problems. The best of these approaches are reviewed in [7, 8] and involve using either:

(i) crack tip elements with the midside nodes moved to the quarter points and with the stiffness matrix computed using reduced integration;

(ii) crack tip elements with the midside nodes moved to the quarter points and all nodes at the crack tip allowed to have different degrees of freedom;

(iii) very small elements at the crack tip with each element having a Young's modulus of unity (this procedure is known as Unimod).

Of these approaches, the first, which we will now term method B, is the simplest and yields very accurate results [8]. The other methods are easy to implement for two dimensional problems but are very tedious to implement for three dimensional problems. The second approach also generates an r^{-1} strain singularity which is only true for an elastic perfectly plastic material.

4. NUMERICAL INVESTIGATION

Let us now consider the applicability of the approaches described above for the solution of a three dimensional elastic–plastic fracture problem. Here, we analyse the distribution of the strain energy density W, and S around a part circular crack in an axially loaded specimen. The specimen is shown in Figure 1 and was chosen to coincide with the specimens tested in reference [9]. The material was taken to obey the stress–strain law,

$$\frac{\epsilon}{\epsilon_0} = 1\cdot932\left(\frac{\sigma}{\sigma_0}\right)^{4.35} \tag{4.1}$$

with

$$\epsilon_0 = 2\cdot175\times10^{-3}$$

and

$$\sigma_0 = 443\cdot4\ \text{MPa}.$$

Because of the symmetrical nature of the problem only 1/4 of the structure was modelled, see Figure 2. The resultant finite element mesh consisted of 12 of the 15-noded isoparametric wedge elements and 249 of the 20-noded isoparametric brick elements. The length scale for the crack tip elements was 1/50 of the tadius of curvarure of the crack front. Two different analyses were conducted. Firstly, in what we term method A, the crack tip elements used were the penalty elements as formulated in Section 3. Secondly, in method B, the crack tip elements had their midside nodes moved to the quarter point positions. The stiffness matrices for all of the elements were evaluated in double precision using reduced integration. The maximum applied stress considered was 177 MPa and at each load level the load steps were varied to ensure that convergence had been obtained. Solutions were performed using the PAFEC suite of finite element programs, on the ARL VAX 11/780 computer.

In order to compare these two approaches, the values of $S\,(= rW)$ around the crack front, are given in Table 1 at three different load levels. Here S is computed from the elements directly in front of the crack.

TABLE 1

Strain Energy Density Function S Around Crack Front

Applied Stress σ MPa	Method	Strain Energy Density Function S (N/m)					
		Position Around Crack					
		1	2	3	4	5	6
88·6	A	230	221	241	253	333	380
	B	234	244	258	283	370	459
132·9	A	879	884	903	935	1200	1362
	B	843	884	899	945	1188	1581
177·2	A	2235	2100	2235	2287	2875	3257
	B	2088	2166	2126	2150	2659	3874

With the exception of point P6 which is a near surface point, both approaches give very similar estimates for S. Indeed as the load increases the discrepancies in these two approaches reduces. This is to be expected since at the lower loads not all of the Gauss points in the crack tip elements had gone plastic.

To assess the validity of equations (2.2), (2.3) and (2.4), which are commonly referred to as the HRR equations, S was also computed indirectly, using equation (3.2), from the opening of the crack. Indeed these values, divided by the value of S at point P1, are shown in Table 2.

TABLE 2

Factorised Strain Energy Density Function S Around Crack Front

Applied Stress σ MPa	Method	Factorised Strain Energy Density Function S/S_{P1}					
		Position Around Crack					
		1	2	3	4	5	6
88·6	A—direct approach	1·00	0·96	1·05	1·10	1·45	1·65
	A—indirect approach	1·00	1·00	1·01	1·05	1·06	1·39
	B—direct approach	1·00	1·09	1·15	1·26	1·65	2·05
	B—indirect approach	1·00	0·99	1·01	1·03	1·23	1·31
132·9	A—direct approach	1·00	1·04	1·07	1·12	1·41	1·88
	A—indirect approach	1·00	0·99	0·98	0·99	1·01	1·32
	B—direct approach	1·00	0·95	1·03	1·07	1·37	1·55
	B—indirect approach	1·00	0·99	0·99	1·02	1·02	1·29
177·2	A—direct approach	1·00	0·94	1·00	1·02	1·29	1·45
	A—indirect approach	1·00	0·98	0·97	0 96	0·96	1·27
	B—direct approach	1·00	1·04	1·02	1·03	1·27	1·85
	B—indirect approach	1·00	1·01	0·97	1·02	1·15	1·29

In general, the variation around the crack is similar with the maximum discrepancy at the lower load levels. As previously mentioned not all of the Gauss points in the crack tip elements were plastic at the lower loads. Since the stress–strain law used in the numerical analysis was a piece wise linear approximation to equation (4.1), it appears that equations (2.2), (2.3) and (2.4) represent a reasonable first approximation. Indeed assuming failure to occur when $S = S_c$, where S_c is the critical value of S for the material, the maximum discrepancy in the computed values of S corresponds to only a 12% difference in failure load.

The computed values of S depend more on the way in which it is evaluated, i.e. by the direct or indirect approach, than on the method by which the solution was obtained, i.e. method A or B. The simplest method is to use isoparametric elements around the crack with their mid-side nodes moved to the quarter points and evaluate W and S directly from the elements in front of the crack tip elements. Reduced integration is recommended when formulating the stiffness for the elements [8].

5. CONCLUSION

This paper has shown that the two dimensional elastic–plastic fracture equations represent a first approximation to the stress and strain fields around a three dimensional crack. As in two dimensional elastic–plastic fracture mechanics, the strain energy density function is relatively insensitive to the method by which it is computed.

6. ACKNOWLEDGEMENT

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* Footnote. It should be noted that the failure load is proportional to $(S)^{1/n+1}$.

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APPENDIX

A Penalty Eelment for Plastic Fracture

In order to enforce the functional form of displacements around the crack tip we use the constrained variational approach detailed in reference [6]. Consider a typical 15 noded isoparametric element at the crack tip, as shown in Figure 3. We wish to enforce equation (2.4) for the nodes along the six radial lines. For simplicity we first investigate the displacement field in one dimension only, as shown in Figure 4. In this simplistic approach the element has three nodes along its length l, with node 1 at the crack tip. We require displacements to be in accordance with equation (2.4), so that

$$u' = a_0 + a_1 r^{1/n+1} + a_2 r^1 \tag{A1}$$

with a_0, a_1 and a_2 as arbitrary constants which are to be determined. Application of the boundary conditions; (i) $u = u_1$ at $r = 0$, (ii) $u = u_2$ at $r = l/2$ and (iii) $u = u_3$ at $r = l$, to equation (A1) yields

$$u' = f_1 u_1 + f_2 u_2 + f_3 u_3 \tag{A2}$$

where

$$f_1 = \frac{-1}{1-2^{(1-1/n+1)}}\left[2^{(1/2-1/n+1)}\left(\frac{r}{l}\right)^1 - \left(\frac{r}{l}\right)^{1/n+1}\right]$$

$$f_2 = \frac{\sqrt{2}}{1-2^{(1-1/n+1)}}\left[\left(\frac{r}{l}\right)^1 - \left(\frac{r}{l}\right)^{1/n+1}\right]$$

$$f_3 = \frac{1}{1-2^{(1-1/n+1)}}\left[\left(\frac{r}{l}\right)^1\left(2^{-(1-1/n+1)} - \sqrt{2}\right) - \left(\frac{r}{l}\right)^{1/n+1}\left(1-\sqrt{2}\right)\right] + 1 \tag{A3}$$

However, in the local isoparametric co-ordinate system X, the displacement field is given by

$$u = -\frac{X}{2}(1-X)u_1 + (1-X^2)u_2 + \frac{X}{2}(1-X)u_3 \tag{A4}$$

We require the displacement field as given by equation (A2) and (A4) to be identical. Thus, the constraint condition to be satisfied is

$$\mathbf{C}(u) = u - u' = 0. \tag{A5}$$

Substituting for u' and u from equations (A2) and (A4) respectively into equation (A5) gives

$$\mathbf{C}(u) = L_1 u_1 + L_2 u_2 + L_3 u_3 \tag{A6}$$

where

$$L_1 = \left[-\frac{X}{2}(1-X) - f_1\right]u_1$$

$$L_2 = \left[(1-X^2)-f_2\right]u_2$$

$$L_3 = \left[\frac{X}{2}(1-X)-f_3\right]u_3$$

$$X = \left[\frac{2r}{l}-1\right]$$

and f_1, f_2 and f_3 are as in equation (A2).

This constraint must be applied to all radial lines in the penalty element, and to all penalty elements around the crack front. The individual constraint equations (i.e. equation (A6)) are combined in matrix form to give

$$\mathbf{C}(u) = \mathbf{L}(u) \tag{A7}$$

where $\mathbf{L}$ is the matrix of constraint coefficients, and $\mathbf{u}$ is the vector of nodal degrees of freedom.

We now build the required constraint condition $\mathbf{C}(u) = 0$, of equation (A7) into the standard finite element method by minimising the constrained complementary potential energy functional Π^*, see reference [6],

$$\Pi^* = \Pi + P\iiint w(x,y,z)\mathbf{C}^{\mathrm{T}}(u)\mathbf{C}(u)dV \tag{A8}$$

which appears in modified form in Section 3. Here Π is the complementary potential energy, P is the penalty number, and w is a positive function. As the penalty number P is increased the constraint condition $\mathbf{C}(u) = 0$ is enforced. Substituting for $\mathbf{C}(u)$ from equation (A7) and differentiating with respect to the nodal degrees of freedom, yields the penalty stiffness matrix

$$K_p = 2P\iiint w(x,y,z)\mathbf{L}^{\mathrm{T}}\mathbf{L}dV. \tag{A9}$$

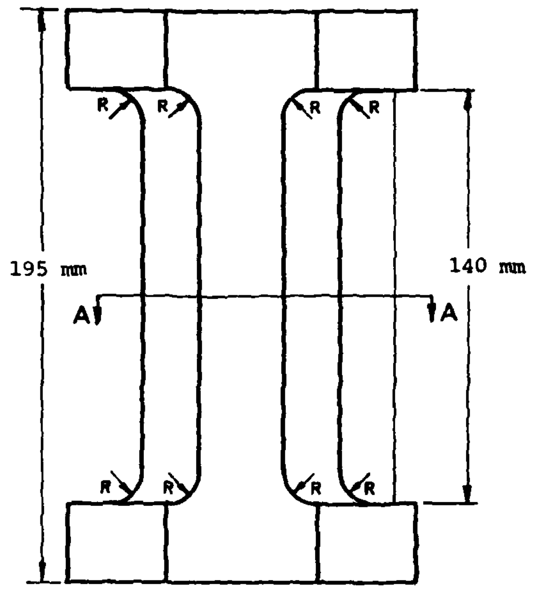

FIG. 1(a) DIMENSIONS OF TEST SPECIMEN

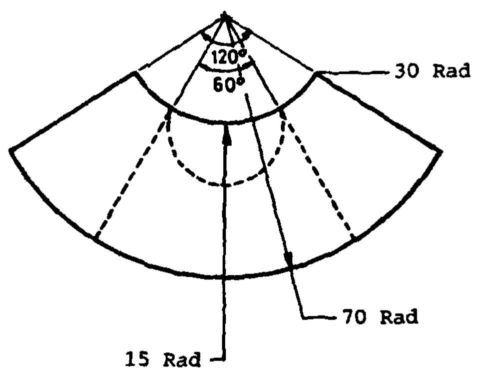

FIG. 1(b) DETAILS OF SPARK MACHINED CRACK AT SECTION A–A.

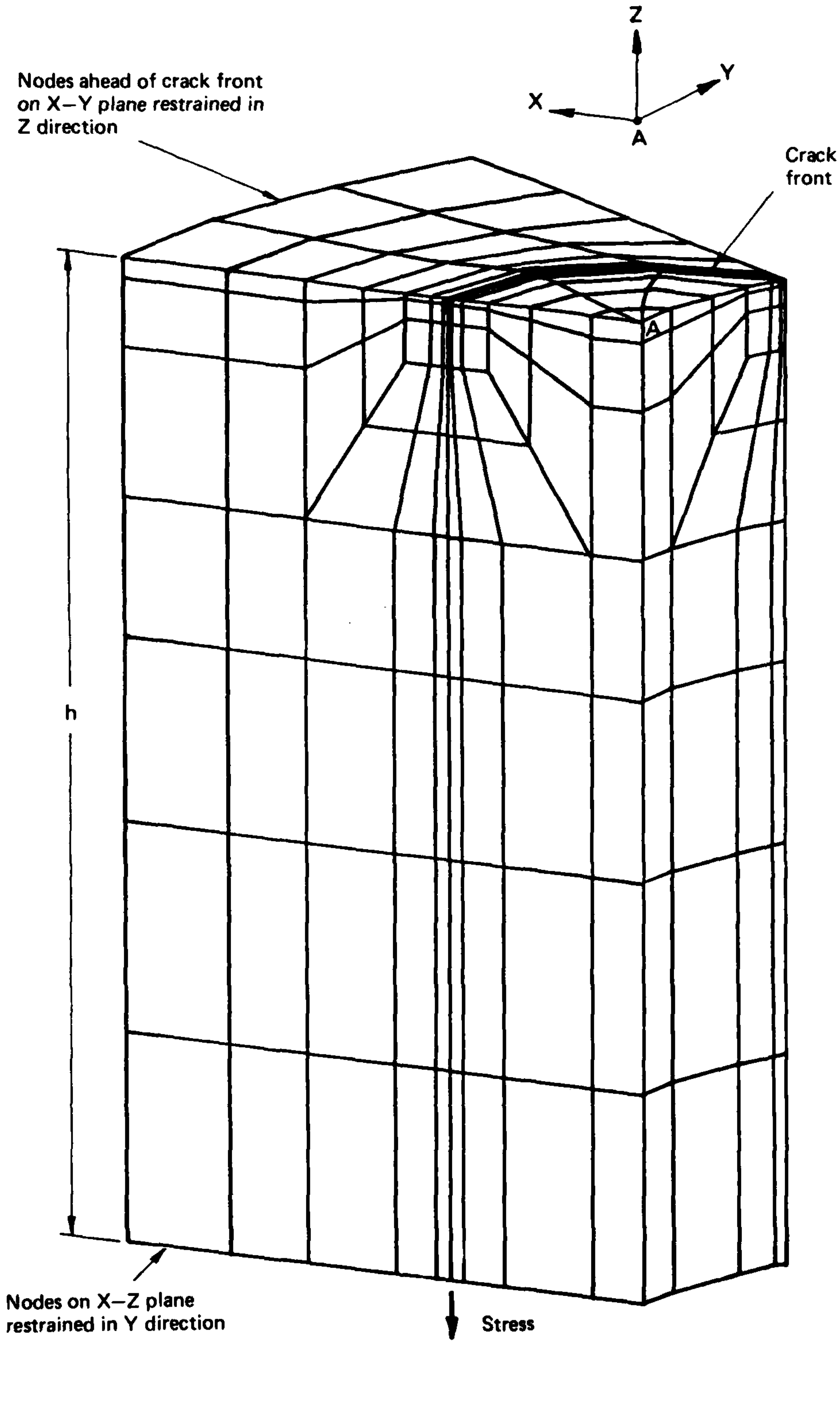

FIG. 2 FINITE ELEMENT MESH

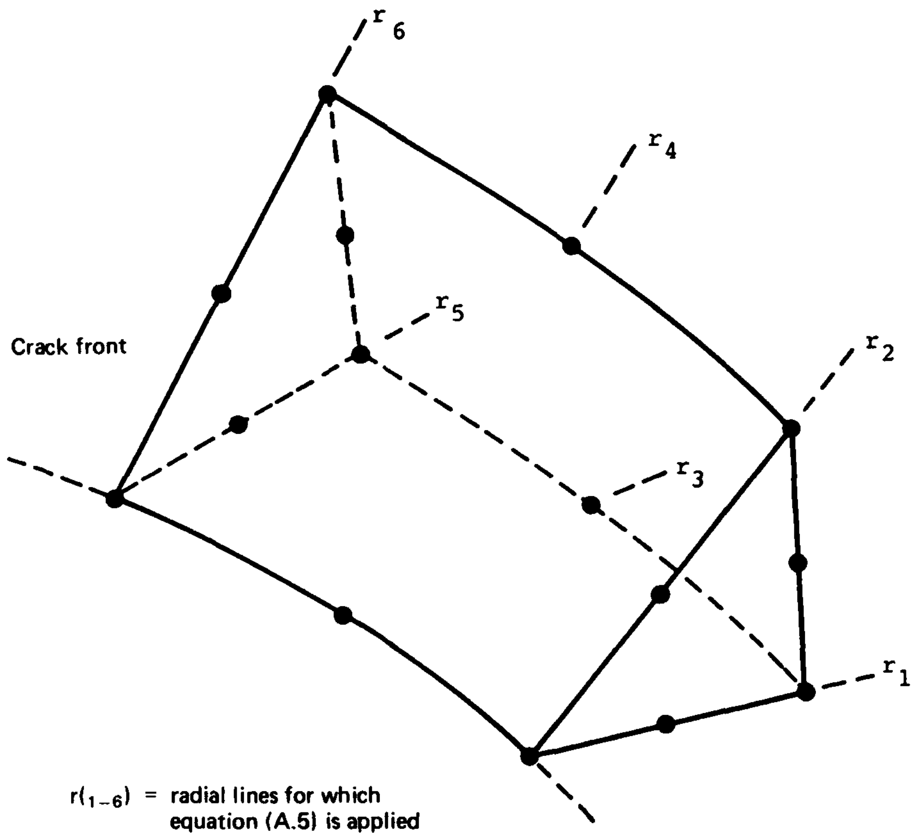

FIG. 3 TYPICAL FIFTEEN-NODED WEDGE ELEMENT AT CRACK FRONT

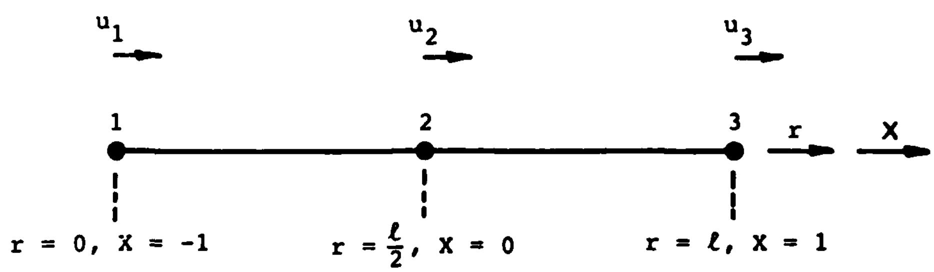

FIG. 4 CO-ORDINATES OF CRACK TIP ELEMENT NODES

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14. Descriptors	15. COSATI Group
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16. Abstract

This paper presents two finite element approaches for the three dimensional elastic–plastic analysis of a surface crack. The distributions of the stress and strain fields around the crack are discussed in detail and it is shown that both approaches yield similar values for the strain energy distribution around the crack.

Keywords: Stress analysis, fracture mechanics, nonlinear propagation analysis, two dimensional, Plastic

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16. Abstract (*Contd*)

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